ETH zürich

LEC

Light Sources for High Volume Metrology and Inspection Applications

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International Workshop on EUV and Soft X- Ray Sources

November 9-11, 2015, Dublin, Ireland

adlyte

Inspection Tools in Semiconductor Industry

Fundamental for wide range of processes (overlay measurements, critical dimensions (CD) control, patterned and un-patterned wafers, masks, defects review).

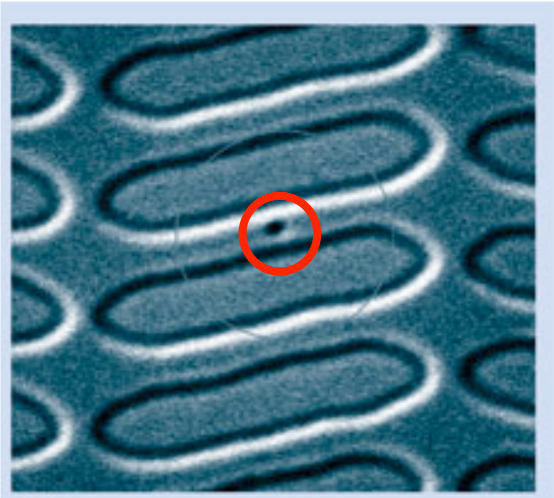
- for process development: sub-nm resolution with low throughput, wide range of defect type detection: **electron beams**

- **Production line: high throughput essential** but with lower sensitivity
- Actinic mask inspections of 1 to 2 hours each
- 100-150 w/hr for un-patterned, 30-50 w/hr for patterned wafer with 10-20 nm sensitivity
- Die to Die comparison and focus on yield-limiting defects (DOI) on 300 mm (450 mm future) wafer sizes

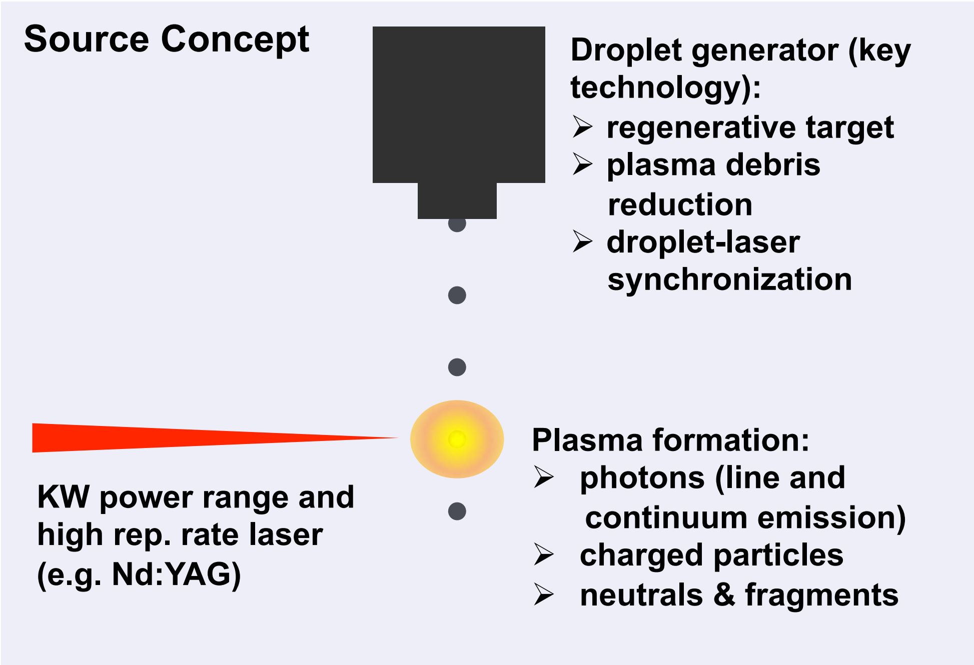
Speed of detection is more important than resolution, focus on particles (main source of defects on IC)

photon beams

lasers or broadband sources facing optical diffraction limit and unique tool not available for all type of defects



LPP in Semiconductor Industry



Advantages:
- High power (watt range)
- High throughput
- Incoherent light emission
- **Emission from the Soft X ray range to the visible range**
- Source Life time
- Brightness (for inspection tools)
- Source Stability

Semiconductor Industry:
- Key technology was previously developed and de-risked for application in EUV Mask Inspection at 13.5 nm with tin droplets (EUV emission at 13.5 nm)

Adaptation and extension to inspection applications:
- Actinic Mask Inspection, Actinic Blank Inspection, Actinic Pattern Inspection
- potential DUV source for sub-20nm defect sensitivity

Some Applications of Light Sources in Semiconductor Industry

Field	Application	Main Strengths
Actinic Inspection	AIMS	stability
	Mask Blank Inspection	Brightness
	Mask Patterned Inspection	COO/Availability
Other Inspections	Wafer Inspection Darkfield	EUV/ DUV
	Wafer Inspection brightfield	Brightness
		COO/Availability

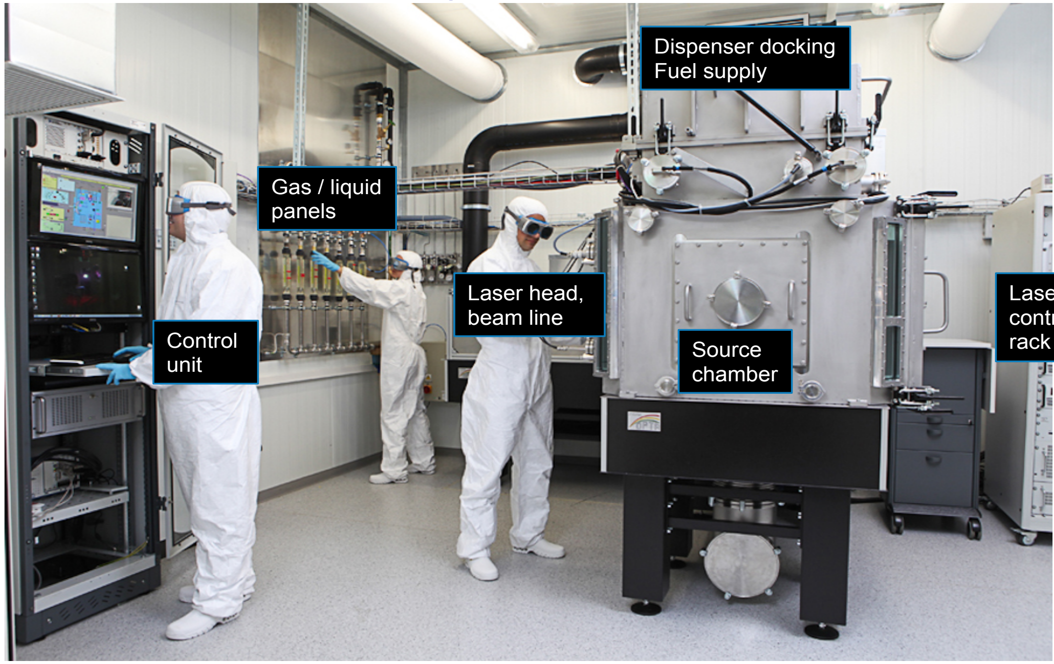
HVM Requirements:

Brightness	> 40 to 250+ (W/mm^2sr)
Uptime	90 to 95%

Pulse to Pulse as well as mean positional and temporal Stability

No debris after IF and match entendue of tool

ALPS II Facility at ETH Zürich



➢ **ALPS II (2013)**

Fully automated facility for long-term operation and lifetime studies (2013)

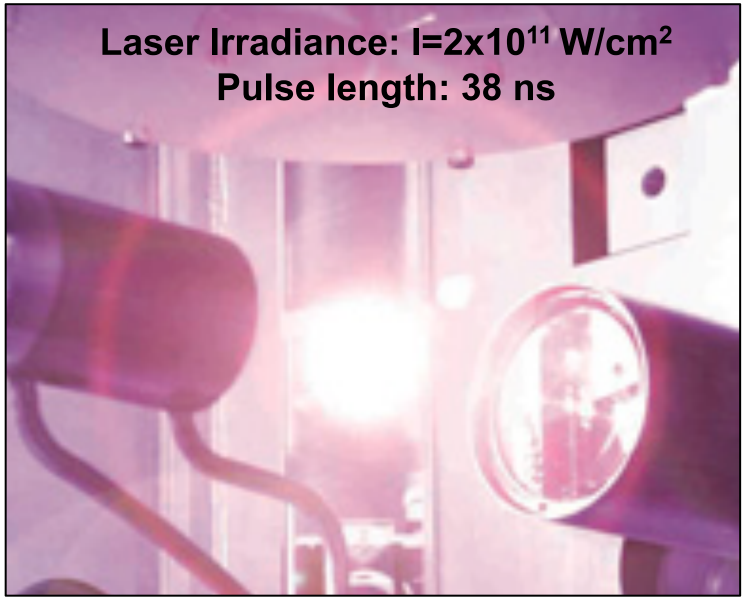
Other facilities:

➢ **ALPS I (2007)**

➢ **DTF-Droplet Test Facility (2009)**

- Nd:YAG Laser: 1.6 kW average power, λ=1.064 µm, 20 kHz rep. rate, typical I=$2x10^{11}$ W/cm^2
- Droplet dispenser with 24hrs run time (30-50 µm droplets with 5-100 kHz)
- Closed loop control system with integrated laser triggering to keep droplets at laser focus position (spatial resolution of ± 5 µm)
- Debris mitigated grazing incidence collector, including clean IF module with imaging capability.
- Plasma diagnostics for charged particles detection and radiation detection (EUV to visible)

Plasma EUV Source Characteristics (ca 2013)



Parameters	Value
Laser power on target (W)	1100
Laser frequency (kHz)	>6
Laser focal spot size (µm)	70 (FWHM)
Conversion Efficiency (CE)	> 1%
EUV source size (µm)	60 (FWHM)
Source power at the source (W)	>12
Source brightness (W/mm^{2}sr)	>350

Recent System level advancements:

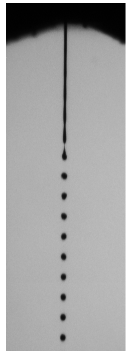
- Emission stability using droplet control in both in time and space
- Debris mitigated EUV collector and Cleanliness validation of tin-based LPP source after IF
- Characterization of source emission (both radiation and debris) with several plasma diagnostics (Langmuir Probe array, EUV pinhole camera, VUV spectrometer)
- Long-term efforts towards other wavelengths, alternative fuels

Alternative Droplet Target Fuels

Indium and Gallium:

- low vapor pressure, high surface tension
- low melting point
- low toxicity
- emission in from 30 nm to 160 nm
- stable jets at low temperatures

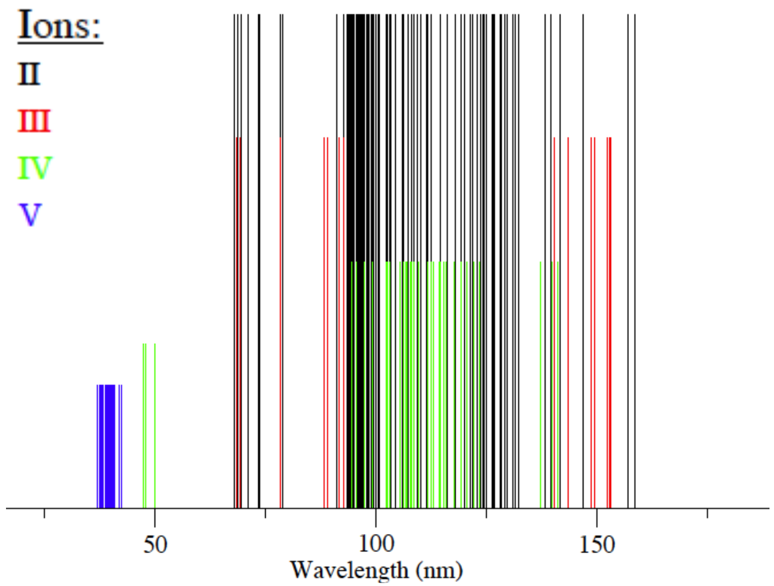
	Sn	Ga	In
Melting Point (°C)	231.9	29.8	156
Surface Tension (dyn/cm)	552	725	556
Vapor Pressure (°C for 1 Pa)	1224	1037	923



Ga droplets @ 70 kHz

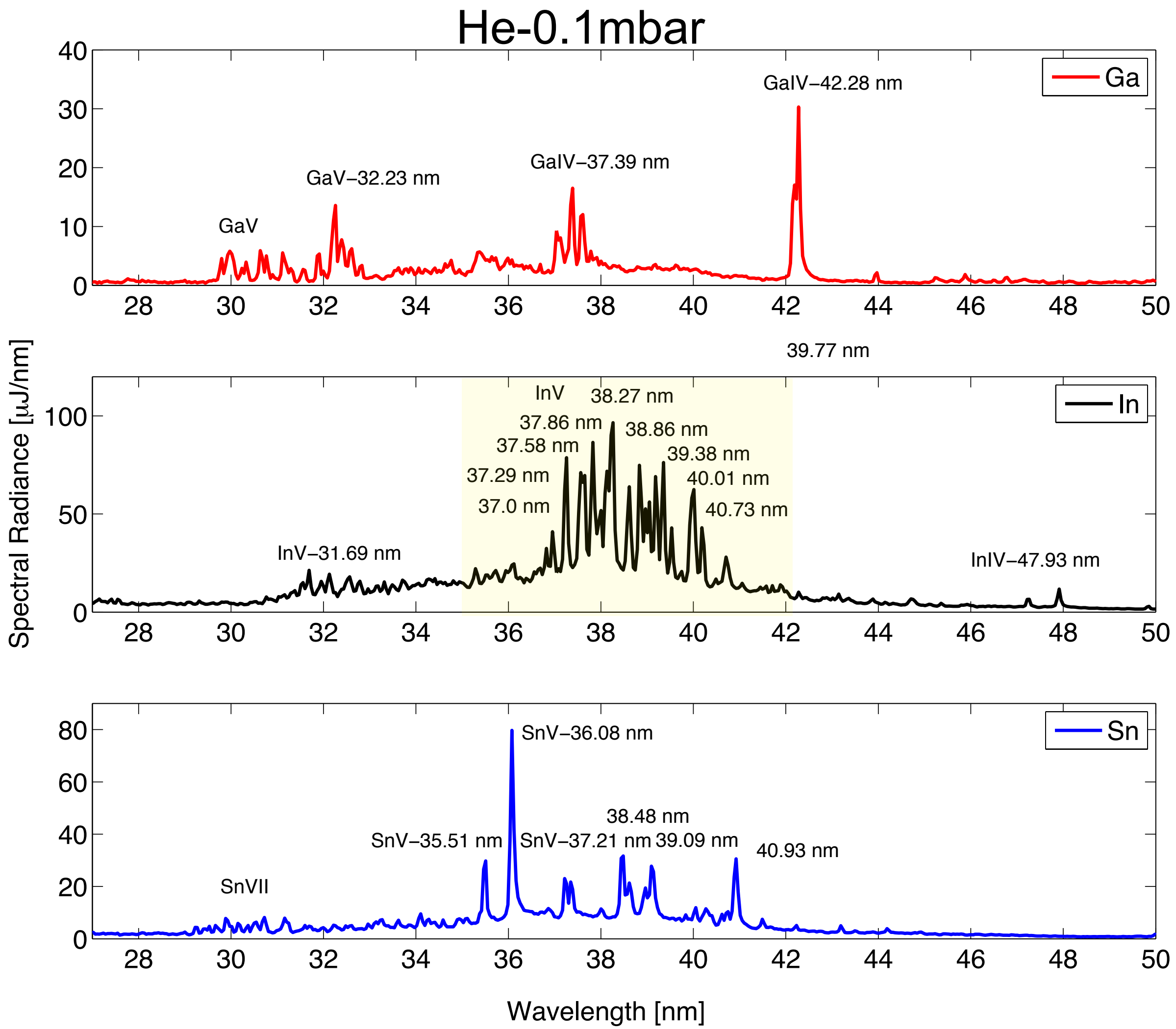
Laser irradiance ϕ vs. desired ion stages, electron temperature T_e and atomic number A:

$$\phi = \left[\frac{Te}{5.2*10^{-6}A^{\frac{1}{5}}}\right]^{\frac{5}{3}} \frac{1}{\lambda^2} \quad \left[\frac{W}{cm^2}\right]$$



InV around 40 nm needs 12 eV, with $\phi \cong 7x10^8$-$9x10^9$ W/cm^2

Example: Ga, In and Sn Spectra at 30 to 50 nm:



- from 30 to 50 nm observed charge states: from 3+<q<6+
- Indium has higher spectral radiance in He with respect to Sn and Ga

Integrated Power (Watt)

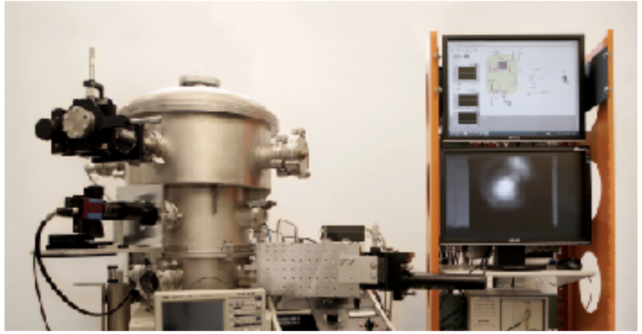
Range (nm)	Ga	In	Sn
30-50	0.27	1.70	0.69
117-137	0.94	1.66	1.34
30-163	2.38	5.8	3.7

Droplet Generation

Droplet generator is a key subsystem of LPP sources

- regenerative targets
- reduction of debris through controlled droplet size
- synchronization of the droplet with the laser pulse

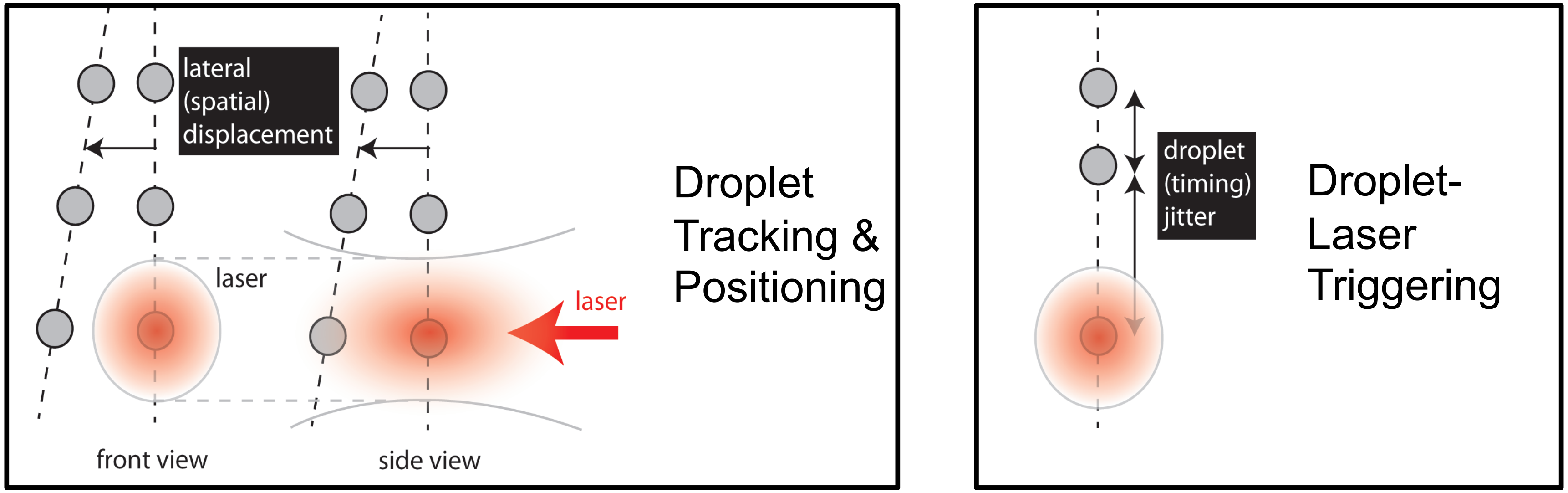
- patented in-house dispenser based on cartridges (including fuel reservoir and nozzle)



Droplet Size	>30 um
Fuel	Pure tin (99.99%)
Droplet frequencies	6-100 kHz
Downtime for cartridge exchange	<1 hour
Run-time	Days
Starting yield	>97% (1 start failure for 32 runs)

Droplet Instabilities and Control

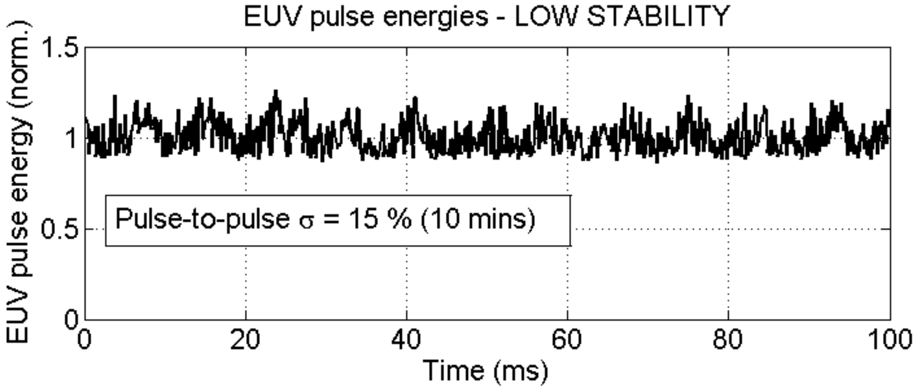
- Droplet stability directly affects the EUV energy stability of the light source

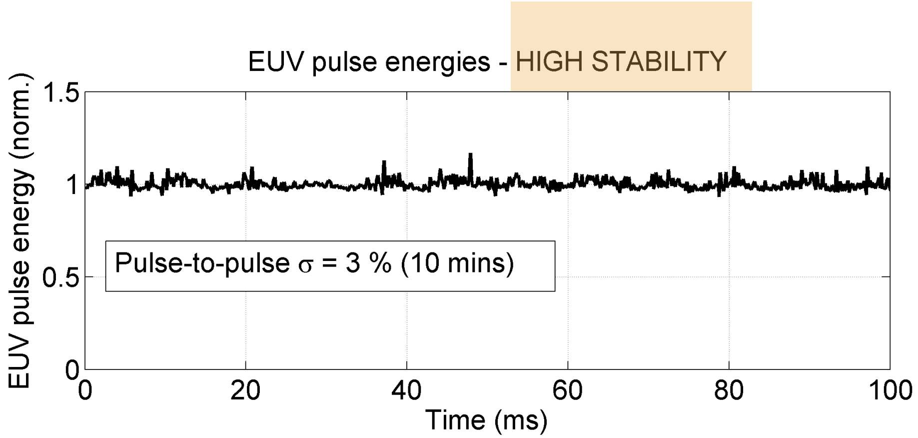


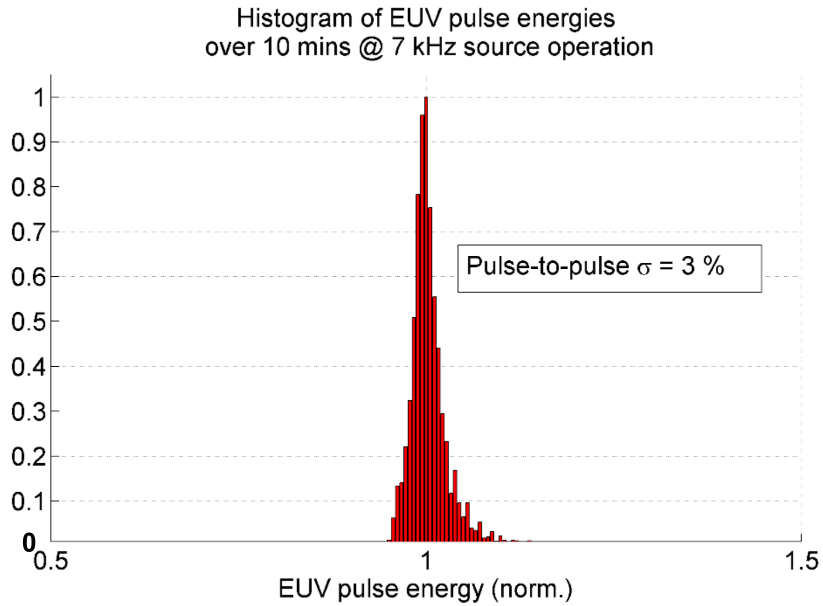
- Major improvements on droplet stability and starting yield have been achieved by quality control of the fuel delivery system

EUV Emission Stability (Raw Signal, no Averaging)

- Integrated EUV pulse energies for 10 mins source operation
- EUV energy monitor (ML, Zr filter) and gated hardware integrator. Source operated at 7 kHz





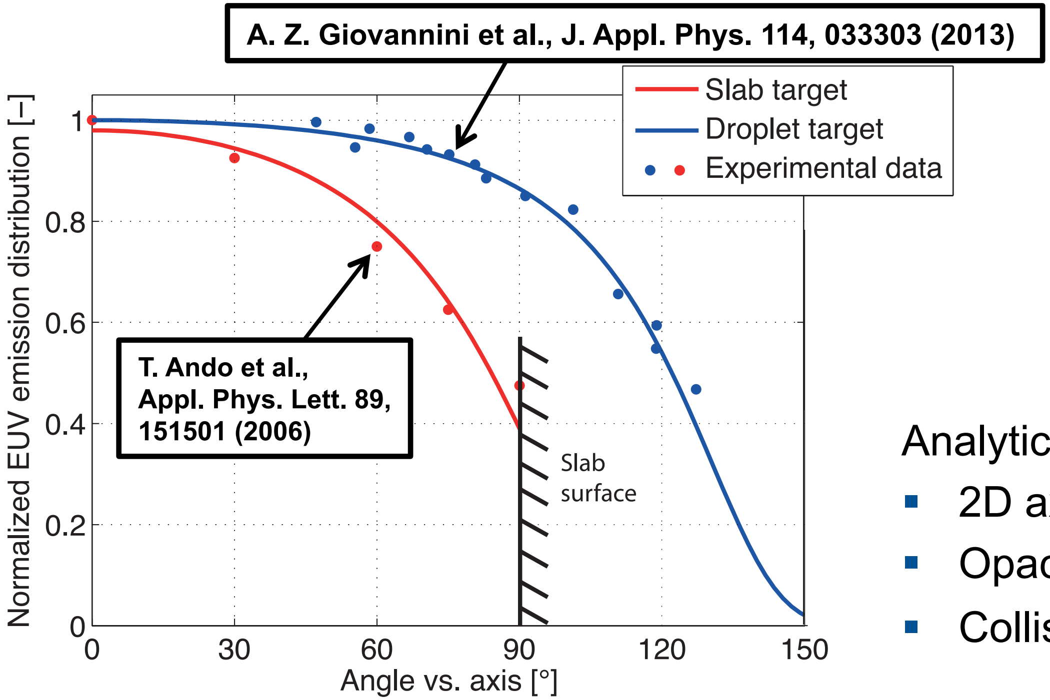


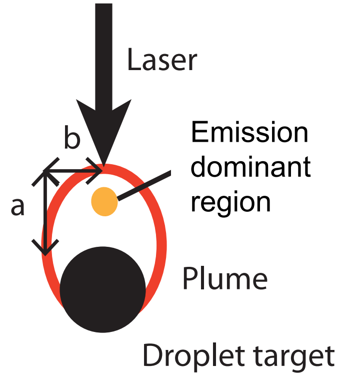
- Pulse-to-pulse stability of EUV energy of 3% (σ) has been recently achieved, due to improvements on droplet tracking / triggering and fuel delivery systems. Typical pulse drop rate ~ 0.01%.

Source Operation and Enhancement Requires Knowledge of Plasma Emission and Debris Load

- Current source produces more power than is currently needed resulting in optimization possibility of collector optics and control systems
- Need to understand how to operate the source for maximum EUV for minimum Debris load
- Systematic numerical and experimental emission and debris analysis, followed by modeling
- Beneficial in tuning our system for improvement in stability and lowering cost of ownership

3D EUV distribution – Difference between droplet and slab targets





Model estimation: ***b/a***=0.8

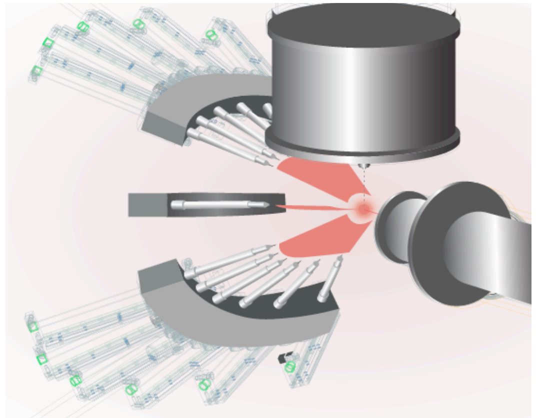
Analytical model solves:

- 2D axis. gas dynamic equations
- Opacity to EUV as a function of *ρ, T*
- Collisional radiative (CR) model

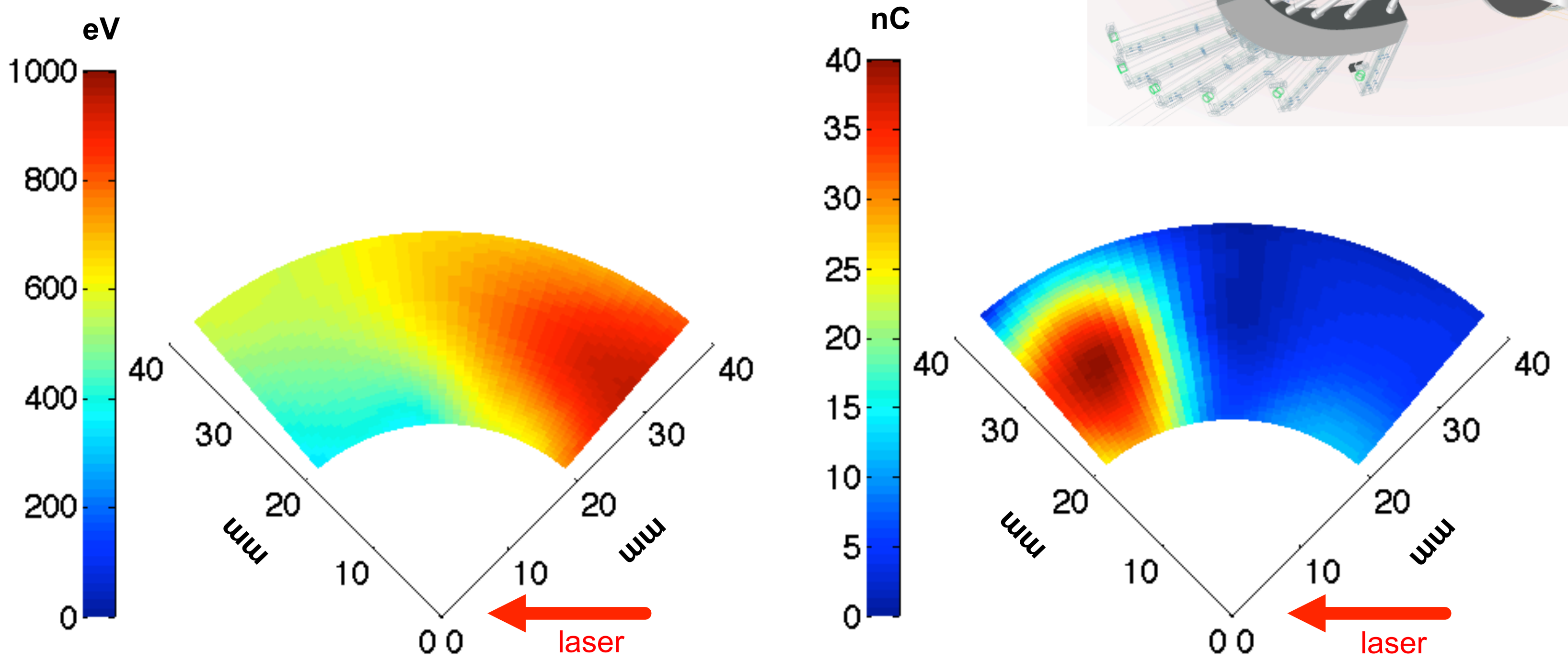
- The analytical model links the plasma shape to the 3D EUV spatial distribution.
- The model is validated with slab target results at the same irradiance ($2x10^{11}$ W/cm^2).
- The plasma shape derived by the EUV distribution is an ellipsoid with *b/a*=1.2 for the slab targets and *b/a*=0.8 for droplet targets.
- From the elongated plasma shape for the droplets, it follows an increase in EUV transmission at large angles.

Angular Distributions of Tin ions

- Tin ion characterization using motorized array of Langmuir Probes



- Distributions of kinetic energy and charge in horizontal plane



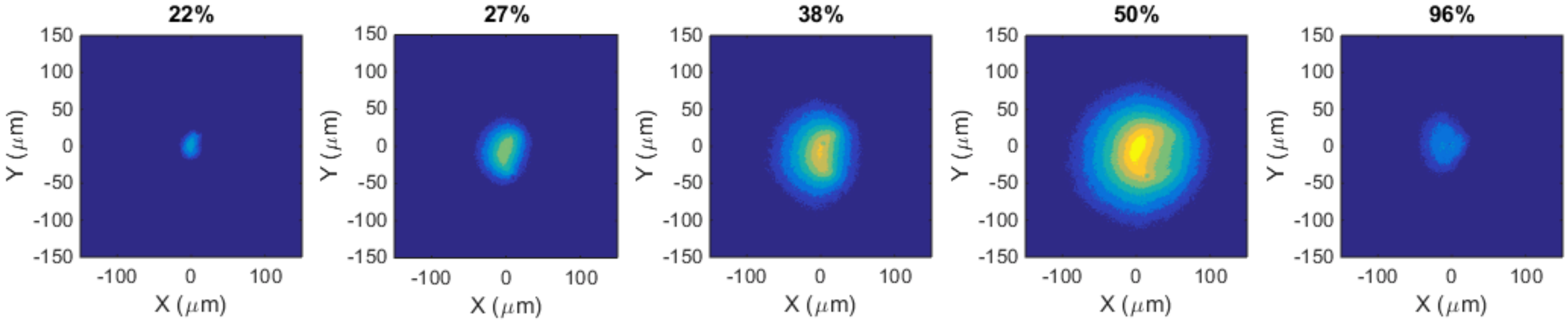
- Largest kinetic energies (damage potential) in forward direction
- Increased abundance of slow ions on the rear side of the target

N. Gambino et. al, Rev. Sci. Instrum. 85 (9), 093302 (2014).

Droplet Plasma Expansion: Measured Images of a Single Event

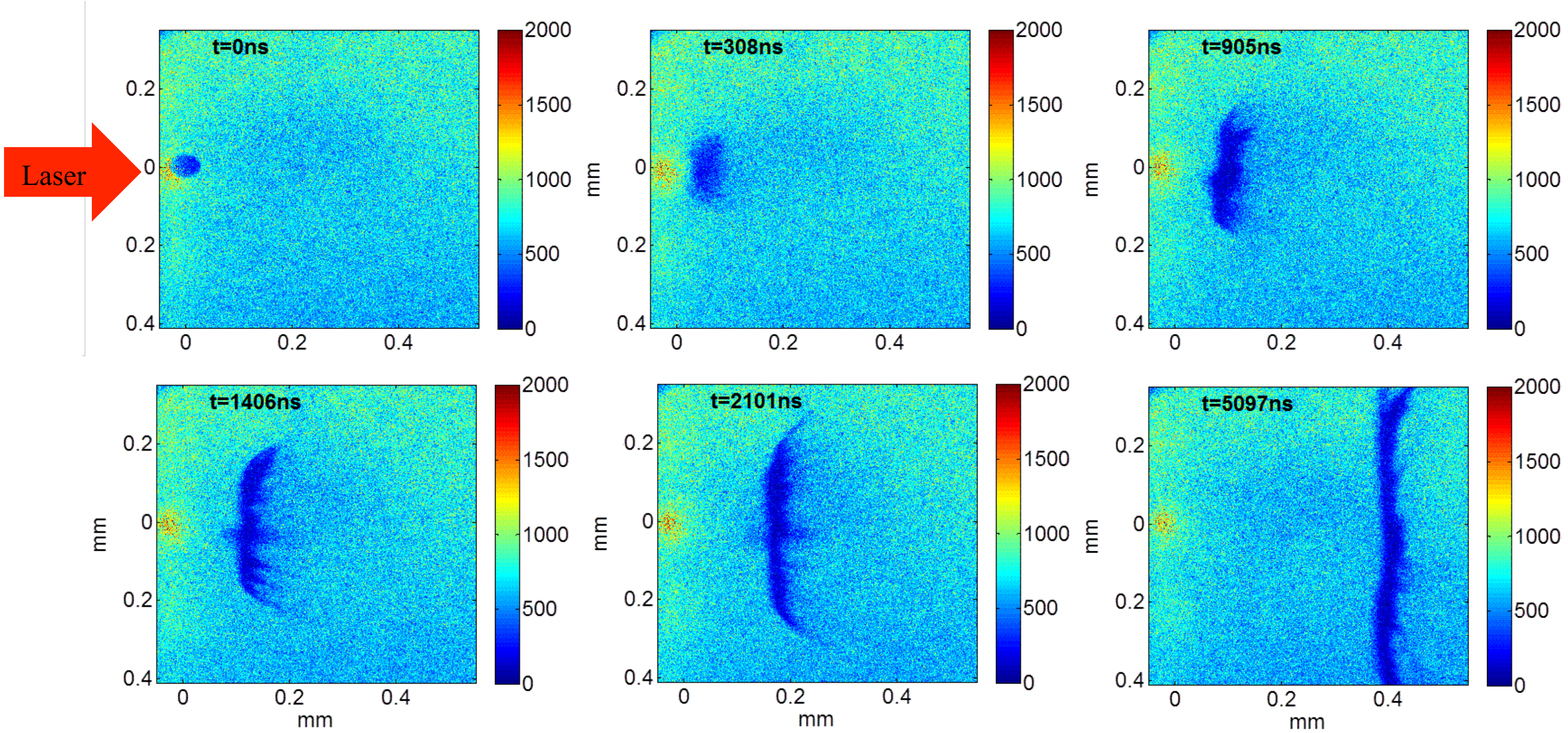
ICCD nanosecond gated imaging in the visible region:

- plasma imaging versus time (% indicates % of laser pulse duration)
- single shot exposure with gate window of 5 ns



- VUV to visible range in coronal plasma, T_e=3-10 eV, n_e=10^{12}-10^{19} cm^{-3} (I-V)

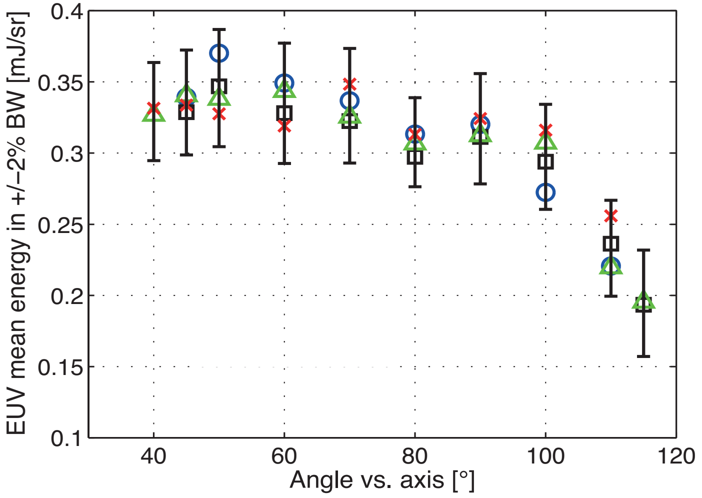
Time-Resolved Debris Imaging with ICCD camera



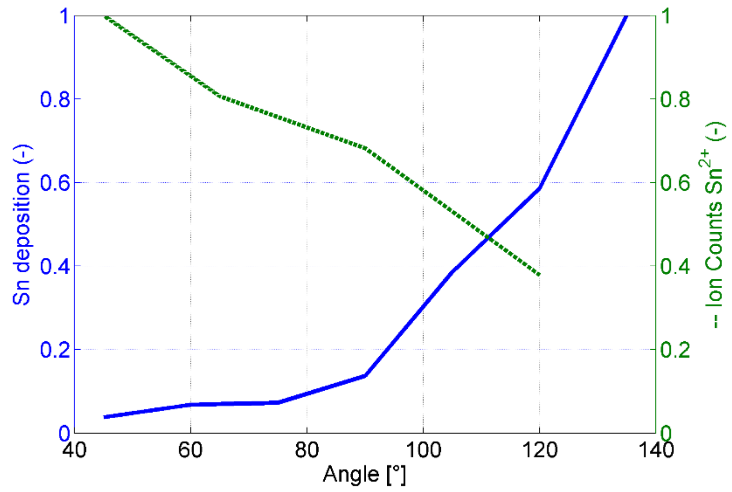
- ICCD exposure time: 250 ns (gate)
- Expansion time calculated from the laser pulse start to the exposure start
- Images captured during continuous source operation at a power of 1.1 kW with individual laser-droplet triggering
- EUV emission recorded for each image

Source Collector Optimum Location

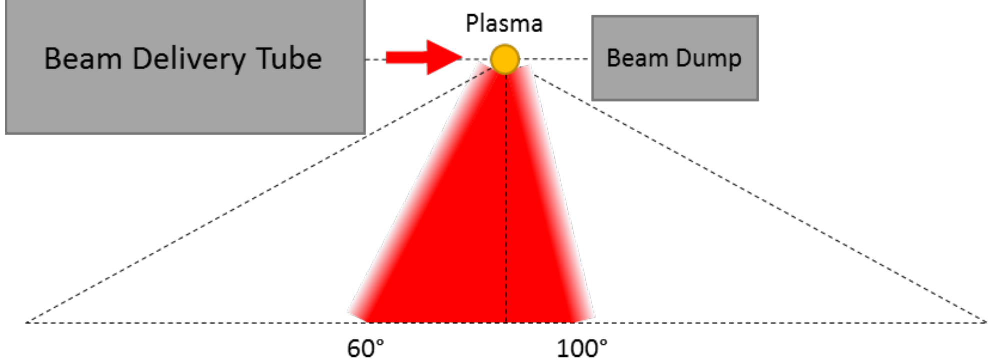
- Optimum location determined by trade-off between emission, neutral and ion debris



A. Z. Giovannini et al., J. Appl. Phys. 114, 033303 (2013).



(*) Si sample exposure
(**) Results from electrostatic analyzer, Diss. ETH A.Z. Giovannini



Debris Mitigation Strategy

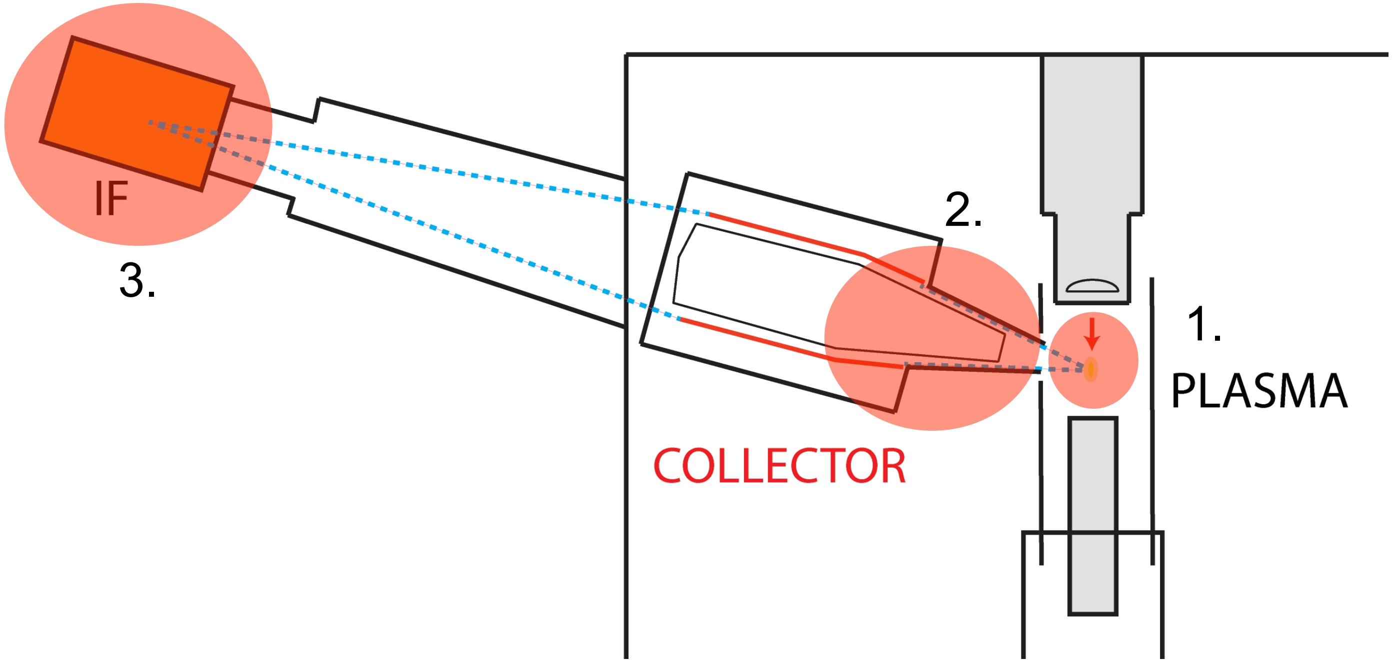
A. Limit debris formation

B. Mitigate debris

LAYER 1. Control debris around plasma

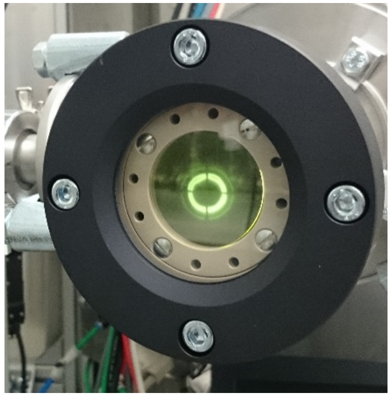
LAYER 2. Control debris in the collector module

LAYER 3. Control debris at IF



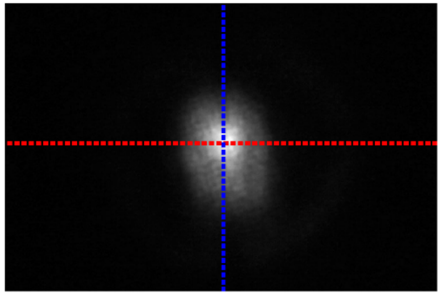
Source Collector Module - Imaging

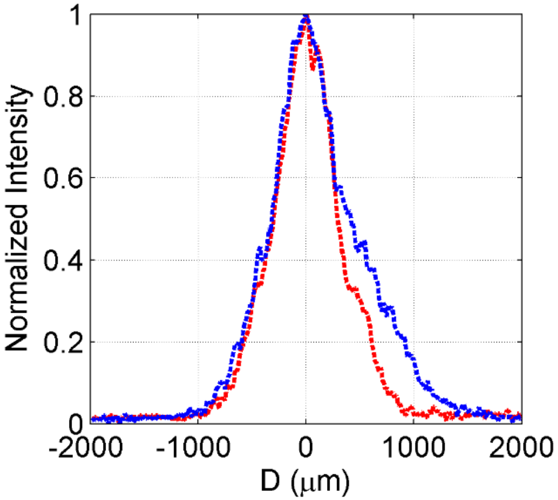
- Imaging for monitoring of alignment, collector reflectivity drop and focal spot uniformity



Collected EUV emission on screen

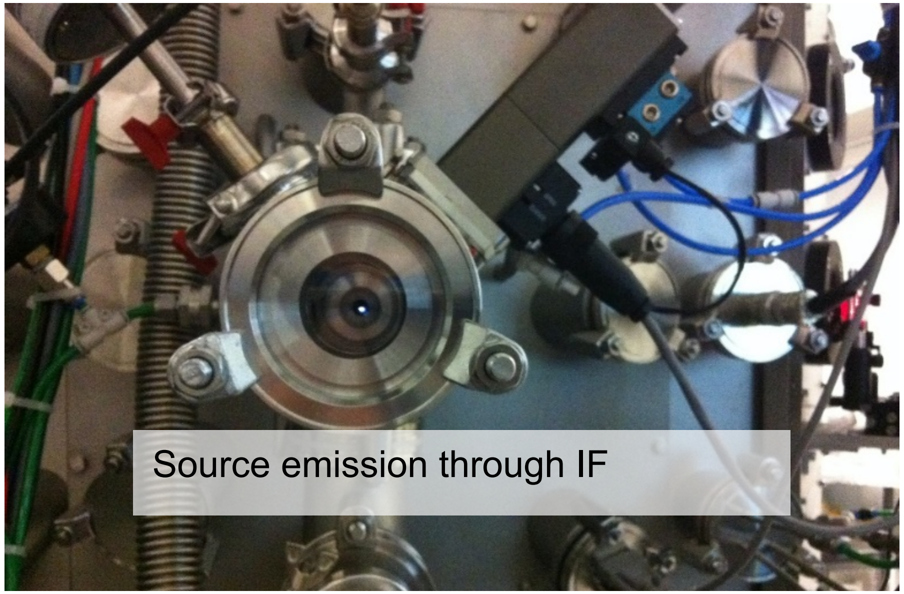
Illuminated collector





Beam uniformity close to IF (FWHM 500 μm)

LPP Source Meets EIDEC Requirements for Blank Mask Inspection Cleanliness after IF



"We are pleased with the cleanliness we measured on Adlyte's light source under conditions that replicate a production environment. This meets our requirements for blank mask inspection."

Hidehiro Watanabe, general manager, **EUVL Infrastructure Development Center (EIDEC)**,

PR 22 October 2014

Status of Actinic Mask Inspection

- Mask Blank and AIMS tools currently under development
- Status of Pattern Mask Inspection (PMI) is open, in light of pellicle for mask as well as as recent industry mergers

- Key driver for tool development is the timing of EUVL HVM
- HVM timing becomes clear with binding financial commitment of end customers

- It takes minimum of 3 to 4 years HVM production ready inspection tool
- First generation of PMI is unlikely to be ready for EUVL HVM

- Light source specs for EUVL HVM Actinic Mask Inspection is challenging, but achievable

Final Remarks

- ETH Zurich will continue improving LPP plasma science and the technology for future generation of light sources for mask and wafer inspection systems.
- All the technology developed here is owned by ETH Zurich and is exclusively licensed to Adlyte AG for commercialization.
- Adlyte is actively engaging with partners (incl. supply chain) on meeting the commercial requirements of the tool makers.
- We would like to thank our team and the industry partners for collaboration and support as well as our supplier for continuing their engagement
- Special thanks to Swiss National Foundation and Swiss CTI for their continued support

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Thank you

Thank you for your attention.